CEIP REPORT NO. 18





# NEWPORT RIVER ESTUARY DYE STUDY: AN ANALYSIS OF WATER MOVEMENT

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ABSTRACT

An investigation of the movement of dye in the Newport River estuary, Carteret County, North Carolina, was conducted in November and December, 1980. Instantaneous introductions of a non-toxic, fluorescent dye, Rhodamine - WT, were made and wind and tidal conditions were recorded. At a number of locations the fluorescence, temperature and salinity of the water was measured at the surface and at a depth of 2 meters. Aerial photographs were taken of the dye plume during portions of this study.

The Atlantic Intracoastal Waterway channel appears to greatly influence the movement of water in the lower part of the Newport River estuary. During the ebb tide, the dye travelled from a point north of the Newport Marshes, within the Intracoastal Waterway Channel, and towards the Beaufort Inlet where horizontal and vertical mixing rapidly reduced dye concentrations. During the flood tide, the dye was dispersed throughout the various channels branching off from the Intracoastal Waterway.

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## SUMMARY AND CONCLUSIONS

Investigation of the movement of dyed water in the Newport River estuary, Carteret County, N.C. indicated that the Atlantic Intracoastal Waterway channel greatly influences the dispersion of water in the estuary. Water traced with Rhodamine - WT, a non-toxic, biodegradable, fluorescent dye, travelled during the ebb tide from a point north of the Newport Marshes, within the Intracoastal Waterway channel, and towards the Beaufort Inlet. During the flood tide, the water was found throughout the various channels branching off from the Intracoastal Waterway and also was found in Bogue Sound, Taylors Creek and the upper estuary. We conclude that dissolved materials released from a point source generally remain in a distinct plume on the ebb tide but are mixed and carried throughout the lower estuary on the following flood tide.

## RECOMMENDATIONS

We recommend that, in managing coastal facilities along the Newport River estuary, the rapid and extensive distribution of water throughout the estuary be recognized. To reduce contaminant dispersion throughout the Newport River estuary and to increase the likelihood for dilution outside the estuary, effluent release should be restricted to periods during ebb tide and sites within the Intracoastal Waterway channel in close proximity to the Beaufort Inlet.

Current meter monitoring stations and dye tracer studies (using the continuous method of dye release) would provide further and more extensive information about circulation patterns and optimum pollution control methods in the Newport River estuary.

## INTRODUCTION

The Newport River Estuary, Carteret County, North Carolina is a highly productive body of water. Annually, it provides a livelihood for several hundred individuals engaged in shrimping, clamming, and oystering. Additional hundreds of individuals derive considerable relaxation and enjoyment from sports fishing during the year. Unpublished data from the North Carolina Division of Marine Fisheries, Morehead City, North Carolina, indicates that in 1978 the wholesale value of the fisheries in the Newport River was $1.2 million.

The Newport River is situated in the center of Carteret County. It is bounded on the north by forest, farmland and several small communities, on the east by the town of Beaufort, and on the southwest by the town of Morehead City and its deep-water port. The Newport River contributes to the economy of Carteret County not only through fisheries and its port but also through the tourism on which the county is dependent. The tourist income in Carteret County in 1979 was, according to the Carteret County Chamber of Commerce, approximately $64 million.

The dye study reported here was designed to aid in the description of the short-term, tidally-driven, movement of water and dispersion of materials in the Newport River estuarine system. It is intended that the information presented here will contribute to a better understanding of the fate of contaminants which might enter this system. To gather information on the dispersion properties of waterborne materials in this tidal system, a dye tracer study was carried out on November 20-22, 1980 and again on December 12-14, 1980. The purpose of this report is to describe the procedure and findings of the study and to discuss the dispersion characteristics of the Newport River estuary.

### Newport River Estuary

The Newport River estuary (34°45N, 76°40W) extends from "The Narrows" of the Newport River to the Beaufort Inlet (Figure 1). The average depth at mean low water is 1.0 m (Williams, 1966) and the estimated volume is $3.079 \times 10^9$ $m^3$ (Hyle, 1976). The primary freshwater source is the Newport River (located west of the "Narrows") which receives freshwater runoff from a watershed of about 310 $km^2$ (Wolfe, 1975). Core Creek, located at the "L" bend, is maintained for navigation as part of the Intracoastal Waterway which passes through the Newport River estuary. No significant thermal or salinity stratification exists in the system (Wolfe et al., 1973). The upper part of the estuary measures approximately 1.7 km in width. This area generally consists of shoals, oyster and clam beds and is a primary nursery area (Figure 2). The downstream end of the estuary is approximately 0.8 km in width, includes the Intracoastal Waterway channel and a deep-water access channel to the port of Morehead City.

Hyle (1976) studied water movement in the Newport River estuary by analyzing the movements of sea bed drifters and determined flushing rates for six segments of the estuary using the tidal prism method. The flushing time for each segment ranged from 1.3 to 2.3 tidal cycles. A total of 12.0 tidal cycles (approximately 6 days) was estimated as the time for Newport

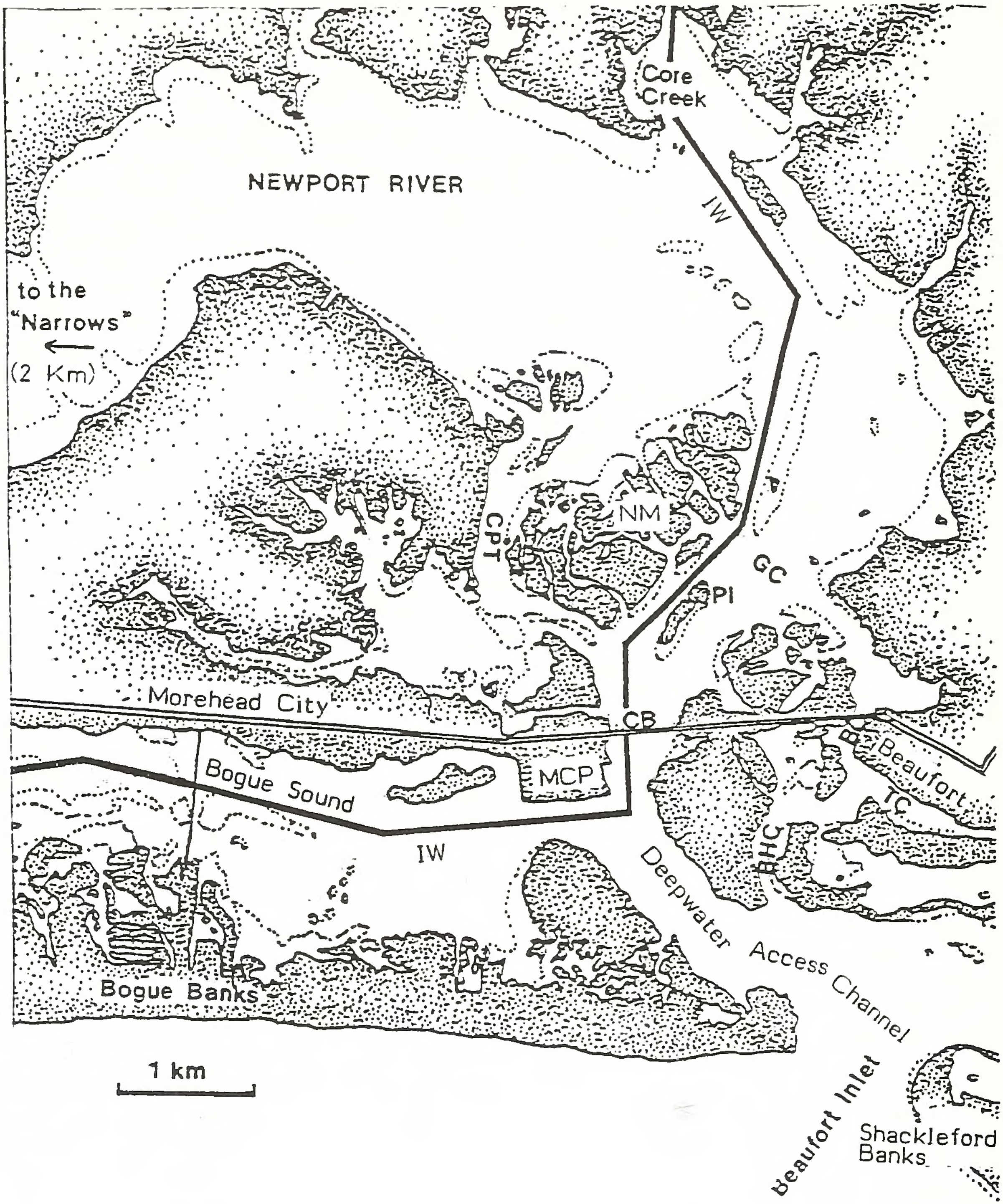


Figure 1. Main body of the Newport River estuary, N.C. and the Intracoastal Waterway (IW). BC = Beaufort Channel, BHC = Bulkhead Channel, CB = Causeway Bridge, CPT = Crab Point Thoroughfare, GC = Gallant Channel, MCP = Morehead City Port, NM = Newport Marshes, PI = Phillips Island, TC = Taylors Creek.


Figure 2. Shellfish and primary nursery areas in Newport River estuary, N.C. From Ducharme and Strickland, 1980, and the North Carolina Division of Marine Fisheries. (NM = Newport Marshes)

River water to move through the estuarine system. Flushing rates are affected by river input, tidal volume changes, evaporation, local topography and prevailing local wind patterns. Hyle (1976) provided information from which one can determine the possible fate of a hypothetical mass of water with respect to time and space. However, in order to determine the horizontal and vertical movements of selected water masses at various times in the tidal cycle, more information is needed than is available from his report.

## MATERIALS AND METHODS

Artificially introduced tracer materials are useful for the purpose of empirically evaluating the distribution of a potential contaminant in time and space resulting from the processes of advection and turbulent diffusion. Dye tracer studies usually involve the use of one of two possible methods of dye release. The continuous method of release generally involves a controlled injection of dye over an extended period of time from a source remote from the receiving area. The instantaneous slug release method involves a point injection of dye after which the movement of the peak dye concentration in the plume is followed in the estuary. Due to the unavailability of large volumes of dye necessary for a continuous method of dye release and a restricted number of persons working on the project, an instantaneous slug release method was used.

A non-toxic, biodegradable fluorescent dye, 20% Rhodamine - WT solution (Crompton and Knowles,* New Jersey), was used. Two experiments involving the introduction of a slug of Rhodamine - WT in the surface layer were conducted on November 20-22, 1980 (Experiment 1) and December 12-14, 1980 (Experiment 2). Dye slugs were released at slack high water and 3 hours after low water in Experiments 1 and 2, respectively, to determine the fate of a mass of water during a tidal cycle.

_In situ_ dye concentrations were determined from a small boat at two depths in the water column, surface and 2 m, at 56 stations (Figure 3). Two Turner Model 110 fluorometers (G.K. Turner Associates,* Palo Alto, California) with continuous flow cells were used. Water was pumped through hoses which were attached to a 2.03 m long PVC pipe (Figure 4). An alternator supplied power to run the fluorometers and pumps during _in situ_ monitoring. Separate tubing systems transported water from each depth through a fluorometer flow cell. The lag time and capacity of the two separate pumping systems were determined. Each fluorometer was calibrated, with the flow cells and alternator, using standard concentrations of Rhodamine - WT (Appendices A.1-A.3). A fluorometer with a cuvette door was also calibrated to enable laboratory analysis of the surface water samples (Appendix A.4). Variations in fluorescence with respect to changes in salinity and temperature were determined. Prior to the dye releases, background fluorescence in the estuary was determined. Identical sampling

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*Mention of a brand name does not constitute endorsement by Duke University Marine Laboratory or the North Carolina Department of Natural Resources and Community Development.


Figure 3. Fluorometric sampling stations(*) 1-55 (Station 56, Core Creek Bridge, is not shown). ✪ = dye release stations for Experiment 1 (35) and Experiment 2 (11). BC = Beaufort Channel, BHC = Bulkhead Channel, CB = Causeway Bridge, CPT = Crab Point Thoroughfare, GC = Gallant Channel, NM = Newport Marshes, PI = Phillips Island, TC = Taylor's Creek.

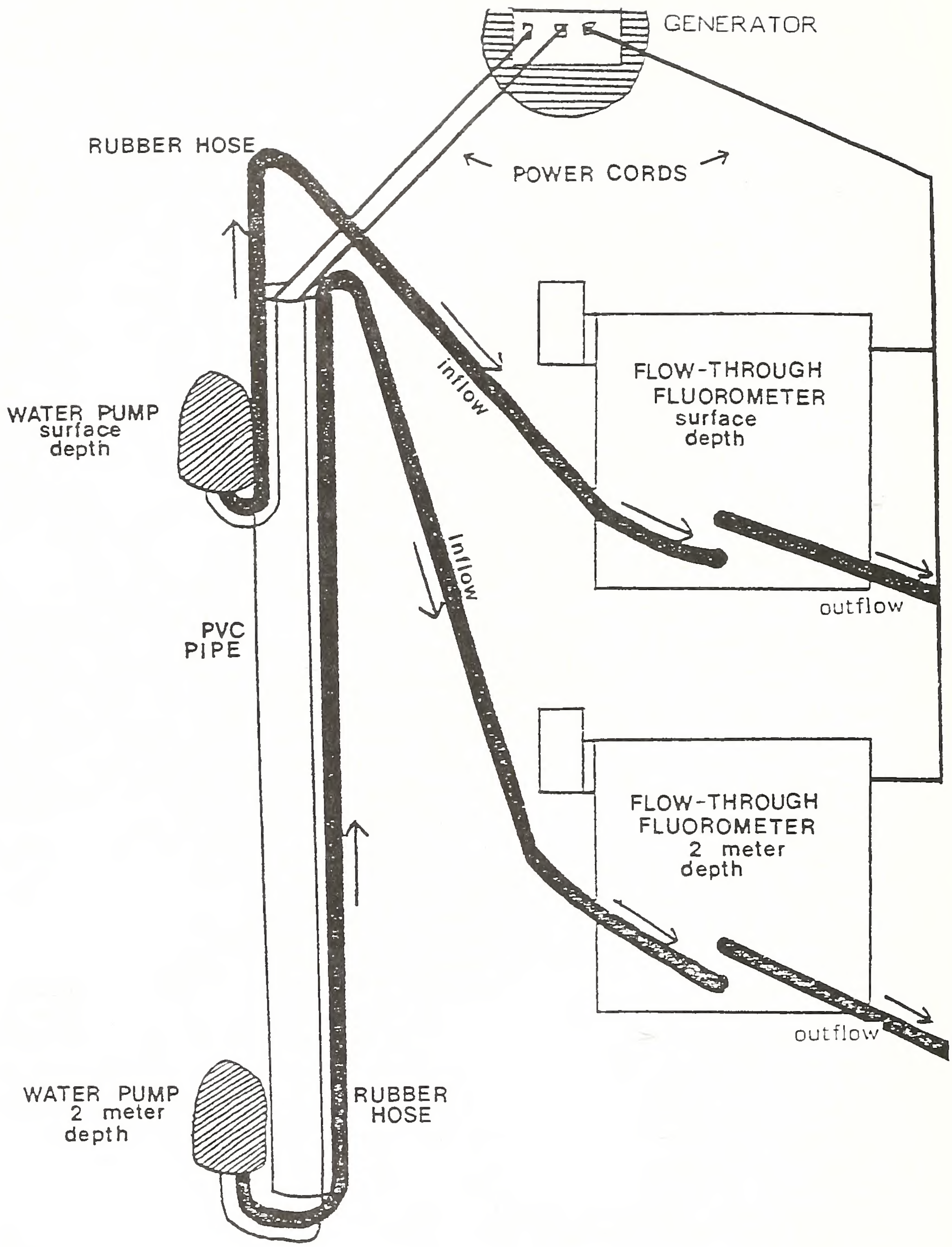


Figure 4. Fluorometric flow-through system (with pumps and generator) for determination of <u>in situ</u> Rhodamine - WT concentrations at surface and 2 m depths.

methods were used in Experiments 1 and 2. In situ monitoring at the surface layer and at depths of 2 meters were carried out by one boat which followed the visible course of the dye plume through the estuary. Another boat travelled to various stations in the estuary at which surface water samples were collected in 15 ml glass bottles for later analysis in the laboratory. A 1-2 day delay in determining the salinity and concentration of Rhodamine - WT in the water samples was observed not to affect concentration. As a precautionary measure against deterioration of the Rhodamine - WT from exposure to light, samples were analyzed as soon as possible after collection. If this was not possible they were stored in a dark room prior to fluorometer analysis.

In many cases Intracoastal Water way channel markers served as monitoring stations during the sampling period. Stations without Intracoastal Waterway markers were marked by buoys set prior to the dye release. Appendix B gives the predicted tide times for the days of the experiments.

## Experiment 1

An instantaneous point release of 5.7 liters of 20% Rhodamine - WT solution was carried out in Experiment 1 during slack high tide at Station 35 (Figure 3). The dye release was made at the rear of the boat so that the boat's propellor would aid in the mixing of the dye. The course of the visible dye plume was followed and point concentrations were determined at preselected stations. A mechanical failure in one of the pumping systems prevented in situ sampling at a depth of 2 m but sampling at the surface layer was possible. Sampling was carried out from Station 35 downstream to Beaufort Inlet where dilution of the dye prevented further tracing. Surface water samples were collected during the flood tide at stations in the estuary and analyzed the following day.

## Experiment 2

An instantaneous point release of 14.0 liters of 20% Rhodamine - WT solution was carried out in Experiment 2, at Station 11 (Figure 3) 3 hours after low water. The dye was introduced as a circular surface patch (diameter 0.02 km) around Station 11. Both pumping systems were in working order during Experiment 2, enabling analysis of water from the surface and a depth of 2 m. In situ sampling was carried out from a boat which followed the visible route of the dye plume. Surface grab samples were collected from another boat as in Experiment 1 and were analyzed later in the laboratory. Surface water samples were also collected from off the boat docks at the North Carolina Division of Marine Fisheries (Station 9), National Oceanographic and Atmospheric Administration (NOAA) laboratory (Station 26), Duke University Marine Laboratory (Station 27) and Core Creek Bridge (Station 56).

Aerial photographs (Photographs 1-5) were taken during Experiment 2 at time intervals within the period of flood tide (LW + 4 h and slack HW). They provided information on the position and distribution of the dye

plume. The aerial photographs further documented the results obtained from the *in situ* sampling from the boat.

## RESULTS

The objective of Experiments 1 and 2 was to determine the distribution of substances entering the Newport River estuary by following the movement of a mass of water which had been tagged with Rhodamine - WT dye.

The prevailing wind in Experiment 1 was 10 knots from the NNE. The sampling method employed and a rapid rate of dispersion in the estuary restricted the analysis of the distribution of dye to point concentrations. The time and distance relative to the initiation time and location for each sampling station was recorded (Table 1).

The visible portion of the dye plume in Experiment 1 remained in the Intracoastal Waterway channel during the ebbing tide (Figure 5). The dye plume travelled at an average rate of 1.27 kph. Instantaneous rates of movement varied according to the state of the tide. Initially the dye plume elongated and formed a narrow ribbon on an east-west axis north of the Newport Marshes (Figure 5). When the eastern end of the ribbon reached the Intracoastal Waterway channel, the dye mass moved within the limits of the channel to south of Station 19 and remained within the Intracoastal Waterway channel enroute to the Beaufort Inlet. The elongation of the plume continued until it reached the Morehead City Causeway Bridge. The width of the plume increased as it passed round the bridge pilings where horizontal and vertical mixing appeared to increase the diffusion of the dye. The concentration in the surface water of the dye plume decreased from 6.5 to 4.1 parts per billion as it moved from north to south of the Morehead City Causeway Bridge.

Fluorometer analysis of surface water samples from the Crab Point Thoroughfare (Stations 15, 32, 22, 26) revealed that, although there was no visible trace of dye in the area west of the Newport Marshes, a small portion of the plume has passed through that area. Thus, while the majority of the traced water followed the Intracoastal Waterway east of the Newport Marshes, a portion had travelled through the shallower Crab Point Thoroughfare west of the Newport Marshes during the ebbing tide (Figure 5).

Estimates of mean concentrations across the plume were not possible due to the extensive length and rapid movement of the dye plume. The edges of the plume were distinct and visible.

A visible dye plume was not observed in the Newport River estuary during the flooding tide in Experiment 1. However, fluorometer delineation of surface water samples clearly revealed the presence of dye in the estuary, indicating that the traced water had remained in the estuary (Table 1). The distribution of dyed water during the flood tide was different from that of the ebb tide (Figure 6). Dyed water appeared to branch off from the Intracoastal Waterway channel at three points. One branch followed a northeastern flow through the Bulkhead Channel, entering Taylors Creek. Traces of dye were found in the Beaufort and Gallant Channels indicating a flow of water into the Intracoastal Waterway at

Table 1. Data collected during Experiment 1 following an instantaneous slug injection of 5.7 liters of 20% Rhodamine - WT solution at Station 35 at high water (HW)+2 hrs 30 min. The concentration of Rhodamine - WT in seawater is presented with regard to tidal period, depth in the water column, location, and salinity.

| Time | | Depth | | Station | Salinity | Conc. |
|---|---|---|---|---|---|---|
| hr | min | Surface | 2 m | No. | °/°° | ppb |
| November 20, 1981 | | | | | | |
| HW+2 | 11 | x | | 36 | | 0.0 |
| HW+2 | 23 | x | | 35 | 33.0 | 0.0 |
| HW+2 | 29 | x | | 34 | | 0.0 |
| HW+2 | 31 | x | | 19 | | 0.0 |
| HW+2 | 36 | x | | 33 | 33.0 | 0.0 |
| HW+2 | 41 | x | | 36 | | 0.0 |
| HW+2 | 43 | x | | 32 | 34.0 | 2.3 |
| HW+2 | 44 | x | | 17 | | 4.0 |
| HW+2 | 45 | x | | 17 | | 1.1 |
| HW+2 | 46 | x | | 17 | | 1.1 |
| HW+2 | 50 | x | | 17 | | 1.1 |
| HW+2 | 51 | x | | 19 | | 1.1 |
| HW+2 | 52 | x | | 19 | | 1.1 |
| HW+2 | 53 | x | | 18 | | 1.1 |
| HW+2 | 53 | x | | 15 | 33.0 | 0.0 |
| HW+2 | 56 | x | | 17 | | 1.0 |
| HW+2 | 56 | x | | 20 | 33.0 | 1.0 |
| HW+2 | 59 | z | | 12 | | 0.0 |
| HW+3 | 3 | x | | 27 | 32.0 | 0.0 |
| HW+3 | 6 | x | | 7 | 34.0 | 0.1 |
| HW+3 | 6 | x | | 20 | | 0.6 |
| HW+3 | 13 | x | | 18 | | 1.1 |
| HW+3 | 14 | x | | 25 | 33.0 | 0.0 |
| HW+3 | 15 | x | | 8 | 34.0 | 0.0 |
| HW+3 | 15 | x | | 22 | 33.0 | 0.0 |
| HW+3 | 16 | x | | 17 | | 1.1 |
| HW+3 | 20 | x | | 36 | 34.0 | 0.0 |
| HW+3 | 25 | x | | 43 | 31.0 | 0.0 |
| HW+3 | 29 | x | | 12 | 33.0 | 6.5 |
| HW+3 | 36 | x | | 12 | 33.0 | 4.1 |
| HW+3 | 41 | x | | 23 | | 0.0 |
| HW+3 | 46 | x | | 15 | 33.0 | 0.0 |
| HW+3 | 51 | x | | 11 | | 1.1 |
| HW+3 | 52 | x | | 11 | | 1.4 |
| HW+3 | 53 | x | | 11 | | 10.0 |
| HW+3 | 59 | x | | 33 | 33.0 | 0.0 |

Table 1. (cont'd)

| Time hr | min | Depth Surface | 2 m | Station No. | Salinity °/oo | Conc. ppb |
|---|---|---|---|---|---|---|
| HW+4 | 0 | x | | 35 | 28.0 | 0.0 |
| HW+4 | 1 | x | | 6 | | 6.3 |
| HW+4 | 6 | x | | 7 | | 6.1 |
| HW+4 | 10 | x | | 7 | 34.0 | 1.1 |
| HW+4 | 11 | x | | 33 | 32.0 | 0.0 |
| HW+4 | 16 | x | | 4-5 | | 1.1 |
| HW+4 | 17 | x | | 34 | 31.0 | 0.0 |
| HW+4 | 20 | x | | 35 | 33.0 | 0.0 |
| HW+4 | 21 | x | | 4-5 | | 1.9 |
| HW+4 | 23 | x | | 5 | | 1.1 |
| HW+4 | 23 | x | | 35 | 31.0 | 0.0 |
| HW+4 | 23 | x | | 34 | 33.0 | 0.0 |
| HW+4 | 24 | x | | 4-5 | | 0.7 |
| HW+4 | 25 | x | | 5 | 34.0 | 0.0 |
| HW+4 | 29 | x | | 33 | 33.0 | 0.0 |
| HW+4 | 30 | x | | 3 | | 1.1 |
| HW+4 | 33 | x | | 2 | | 1.1 |
| HW+4 | 35 | x | | 2 | | 1.1 |
| HW+4 | 36 | x | | 2 | 33.0 | 3.6 |
| HW+4 | 41 | x | | 36 | 32.0 | 0.0 |
| HW+4 | 43 | x | | 32 | 31.0 | 0.0 |
| HW+4 | 50 | x | | 25 | 33.0 | 0.0 |
| HW+5 | 7 | x | | 31 | 33.0 | 0.0 |
| HW+5 | 14 | x | | 3 | 34.0 | 0.0 |
| HW+5 | 21 | x | | 7 | 34.0 | 0.0 |
| HW+5 | 24 | x | | 27 | 31.0 | 0.0 |
| HW+5 | 27 | x | | 12 | 33.0 | 0.0 |
| HW+5 | 43 | x | | 1 | 33.0 | 0.0 |
| HW+5 | 51 | x | | 3 | 33.0 | 0.0 |
| LW+ | 1 | x | | 31 | 33.0 | 0.0 |
| LW+ | 19 | x | | 1 | 34.0 | 0.0 |
| LW+ | 38 | x | | 1 | 33.0 | 0.0 |
| LW+ | 40 | x | | 2 | 33.0 | 0.0 |
| LW+ | 42 | x | | 3 | 33.0 | 0.0 |
| LW+ | 45 | | x | 5 | 32.0 | 0.0 |
| LW+ | 48 | | x | 7 | 33.0 | 0.8 |
| LW+ | 51 | | x | 8 | 34.0 | 3.0 |
| LW+ | 55 | | x | 12 | 32.0 | 0.1 |
| LW+1 | 0 | | x | 15 | 32.0 | 0.5 |
| LW+1 | 5 | | x | 18 | 32.0 | 0.4 |
| LW+1 | 9 | | x | 20 | 31.0 | 1.3 |
| LW+1 | 12 | x | | 21 | 31.0 | 0.7 |
| LW+1 | 16 | x | | 22 | 33.0 | 0.0 |

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Table 1. (cont'd)

| Time hr | min | Depth Surface | 2 m | Station No. | Salinity °/°° | Conc. ppb |
|---|---|---|---|---|---|---|
| LW+1 | 19 | x | | 23 | 32.0 | 0.0 |
| LW+1 | 22 | x | | 24 | 33.0 | 0.0 |
| LW+1 | 26 | x | | 25 | 33.0 | 0.0 |
| LW+1 | 30 | x | | 27 | 33.0 | 0.7 |
| LW+1 | 33 | x | | 30 | 34.0 | 0.1 |
| LW+2 | 18 | x | | 26 | 33.0 | 0.6 |
| LW+2 | 20 | x | | 25 | 33.0 | 0.2 |
| LW+2 | 25 | x | | 22 | 33.0 | 9.8 |
| LW+2 | 27 | x | | 20 | 34.0 | 1.7 |
| LW+2 | 29 | x | | 36 | 31.0 | 0.2 |
| LW+2 | 31 | x | | 36 | 33.0 | 0.8 |
| LW+2 | 33 | x | | 44 | 33.0 | 0.5 |
| LW+2 | 37 | x | | 35 | 32.0 | 0.3 |
| LW+2 | 42 | x | | 43 | 32.0 | 14.8 |
| LW+2 | 53 | x | | 51 | 29.0 | 0.2 |
| LW+3 | 5 | x | | 34 | 33.0 | 0.0 |
| LW+3 | 7 | x | | 33 | 34.0 | 0.0 |
| LW+3 | 11 | x | | 32 | 34.0 | 0.4 |
| LW+3 | 16 | x | | 15 | 33.0 | 0.0 |
| LW+3 | 19 | x | | 12 | 34.0 | 0.0 |
| LW+3 | 23 | x | | 7 | 34.0 | 0.0 |
| LW+3 | 25 | x | | 5 | 34.0 | 0.3 |
| LW+3 | 27 | x | | 3 | 34.0 | 0.5 |
| LW+3 | 32 | x | | 31 | 34.0 | 0.1 |
| LW+3 | 34 | x | | 27 | 34.0 | 0.0 |

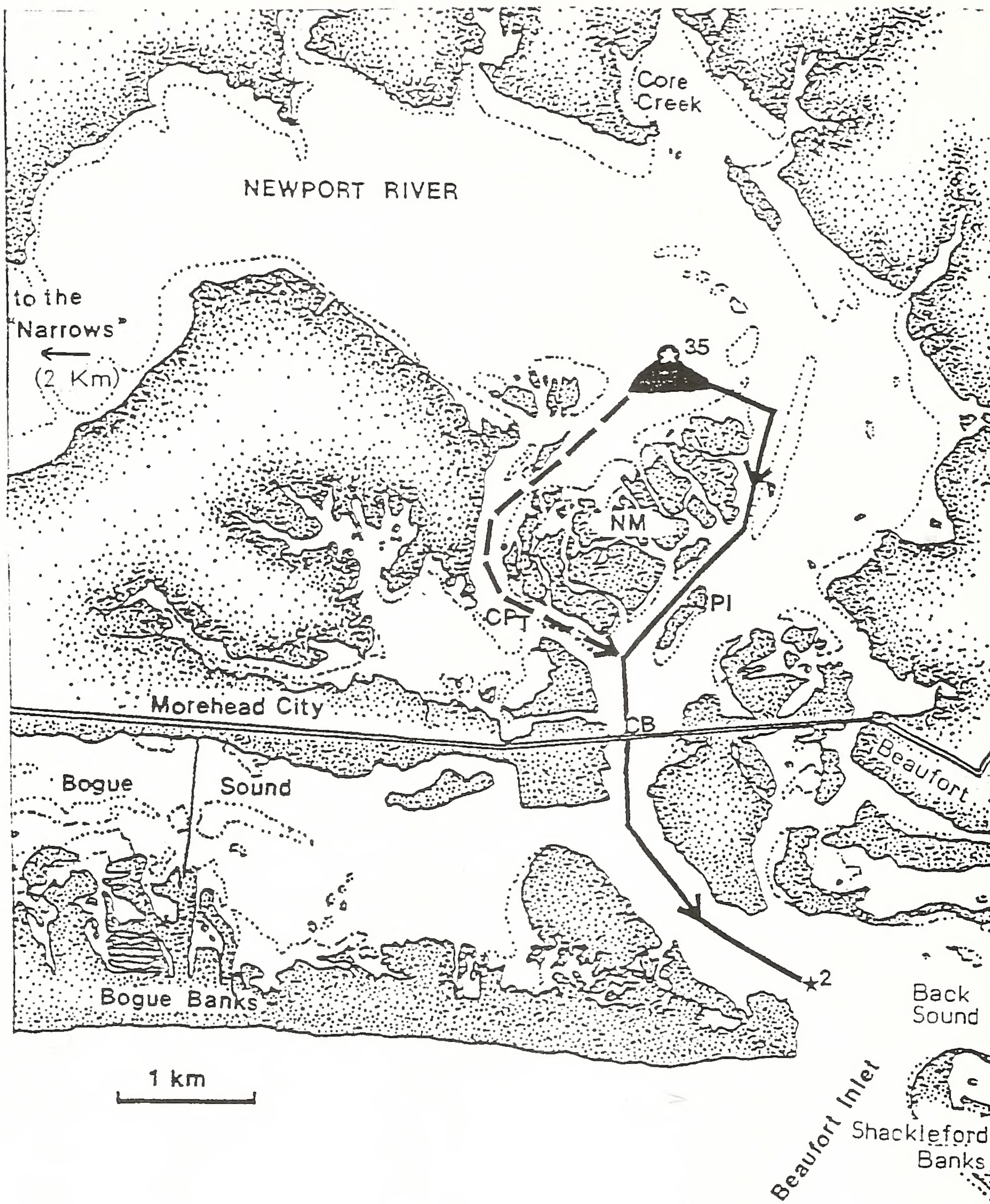



Figure 5. Results of Experiment 1 (ebb tide). Injection of 5.7 liters of 20% Rhodamine - WT solution at Station 35 at high water + 2-1/2 hours. The visible route of the traced water mass during the falling tide is indicated by a solid line. The dashed line indicates the route of traced water through the Crab Point Thoroughfare. ⊛ = dye release (Station 35). CB = Causeway Bridge, CPT = Crab Point Thoroughfare, NM = Newport Marshes, PI = Phillips Island.

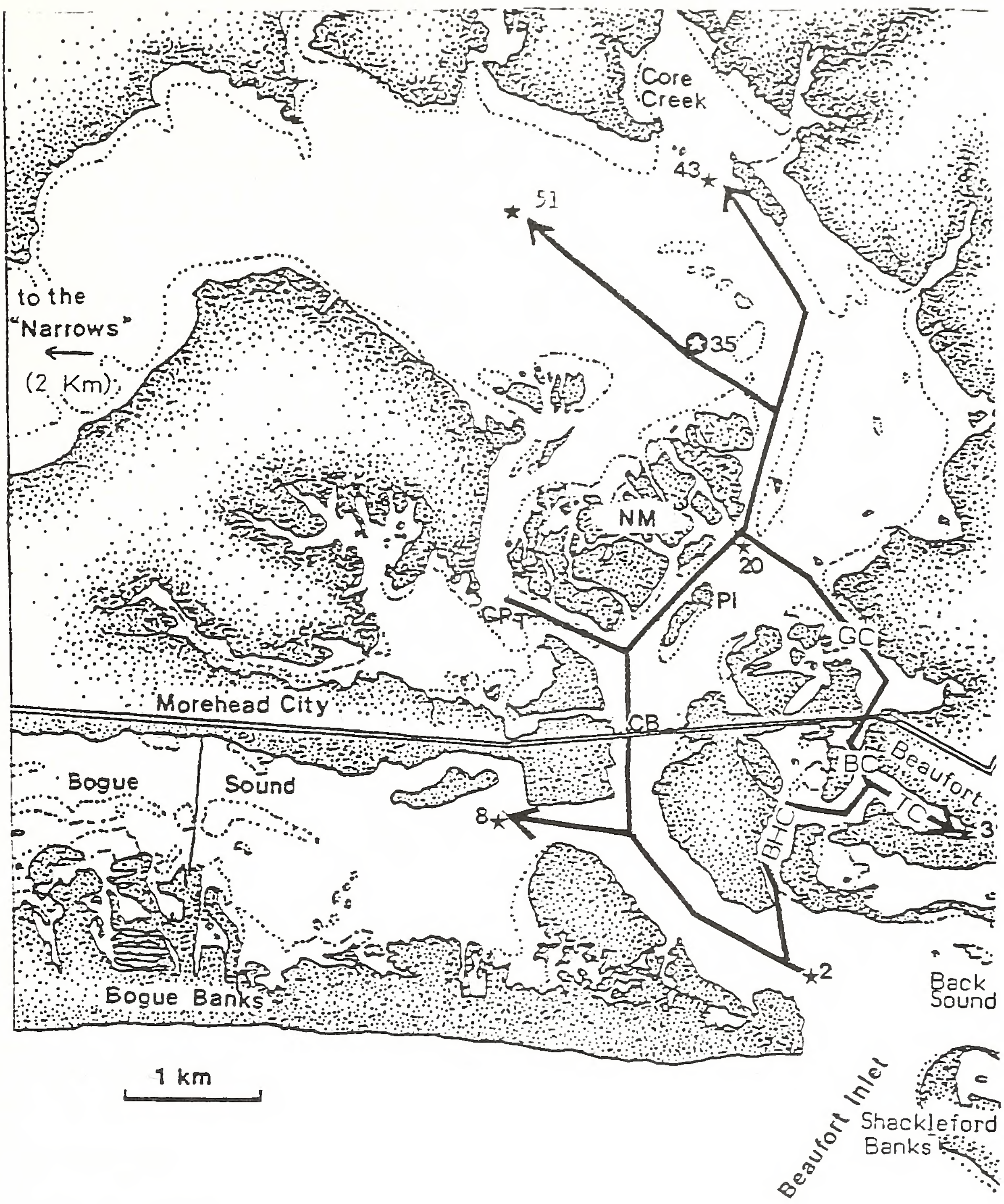



Figure 6. Results of Experiment 1 (flood tide). Instantaneous slug injection of 5.7 liters of 20% Rhodamine - WT solution at Station 35 at high water + 2-1/2 hours. Solid lines indicate the route of the traced water during the flood tide 5-9 hours after the dye was released. ✪ = dye release (Station 35). BC = Beaufort Channel, BHC = Bulkhead Channel, CB = Causeway Bridge, CPT = Crab Point Thoroughfare, GC = Gallant Channel, NM = Newport Marshes, PI = Phillips Island, TC = Taylor's Creek.

Station 20. A second branch separated from the ebb route and entered Bogue Sound. A relatively high concentration of dye (3.0 parts per billion) was found at Station 8 while the tide was still rising, which indicates a possible strong flow of water into Bogue Sound. A third route of dye was to the west of the Newport Marshes through the Crab Point Thoroughfare. The presence of dye was found at the release point, Station 35, and at a point near the nursery area, Station 51. Although it was not possible to sample water in Back Sound it is probable that a fourth branch of water entered this area during the flooding tide.

In Experiment 2 the dye plume was released at Station 11, south of the Morehead City Causeway Bridge. The wind was 10-15 knots SW. The dye plume generally remained within the boundaries of the Intracoastal Waterway as it travelled upstream to Station 36 (Figure 7). The plume moved outside and west of the channel at Station 36 and approached the shoal area northeast of the Newport Marshes. The plume's surface area increased at slack high water and remained in a shallow area outside and to the west of the Intracoastal Waterway, north of the Newport Marshes and south of Core Creek. The dye plume travelled from the releasing point (Station 11) to Station 35 at an average rate of 1.66 km/hr. Surface water samples collected every hour at Core Creek Bridge (6.25 km north of Station 43) during December 12-14, 1980 indicated that the dyed water did not travel to that point in the surface layer. Similarly, surface water samples collected from the boat docks at Stations 9, 26 and 27 showed no presence of dye during the sampling period. Data collected during Experiment 2 are given in Table 2.

Salinity ranged from 29.0 to 34.0 ppt during Experiment 1 and from 16.2 (at Core Creek Bridge) to 36.0 ppt during Experiment 2 (Tables 1 and 2). Laboratory experiments revealed that the temperature and salinity ranges in the Newport River estuary had little effect on the fluorescence of standard concentrations of Rhodamine - WT and thus no corrections were necessary.

*In situ* point determination of fluorescence in the water at the surface layer and at a depth of 2 meters revealed that concentrations of dye were greater at 2 m depth in the water column. Although the various parameters involved in vertical distribution of the dye make it difficult to assess the reason for the difference in dye concentrations, these findings may be partly attributed to the greater density of Rhodamine - WT (1.2 gm/ml) with respect to water.

Aerial photographs taken during Experiment 2 showed that the dye plume generally remained within the limits of the Intracoastal Waterway during the rising tide (Photographs 1-3) and spread out over an extensive area of shallow waters north of the Newport Marshes at slack high water (Photograph 4). These results correspond to those found by *in situ* sampling from the boat. The photographs show the elongation of the plume in the direction of the current flow and revealed that the plume travelled along the eastern boundary of the channel as it passed Phillips Island. Current meter data for the lower Newport River estuary are available (U.S. Geological Survey 1976) and are presented in Figure 8 and Appendices C.1-C.3. The information for a station near Phillips Island (10) to the east of the Intracoastal Waterway show a reversing

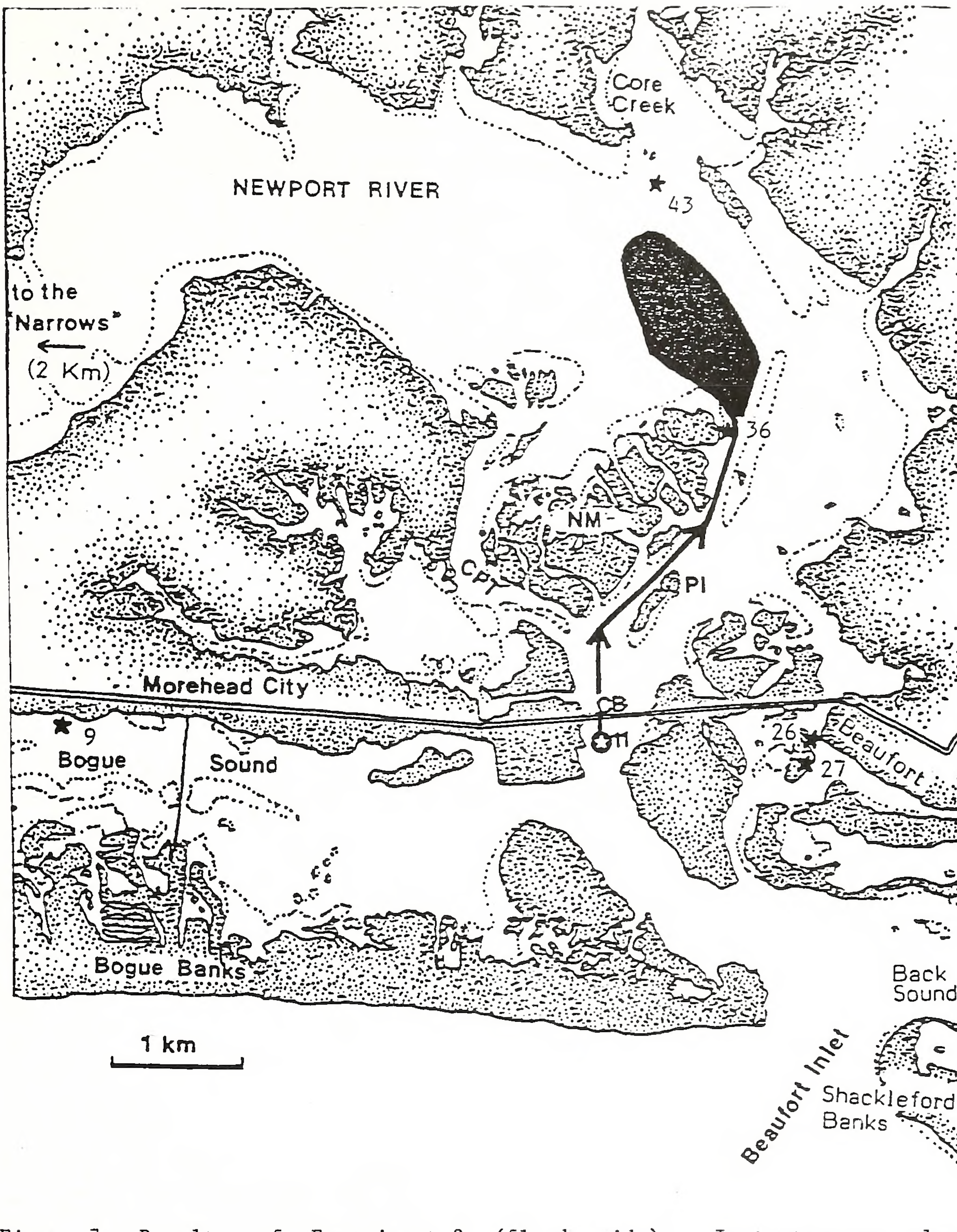



Figure 7. Results of Experiment 2 (flood tide). Instantaneous slug injection of 14.0 liters of 20% Rhodamine - WT solution at Station 11 3 hrs after low water. Prevailing wind was 10-15 knots SW. The period and rate of travel from Station 11 to Station 35 was 3 hrs and 1.72 km/hr, respectively. The dye plume covered a large area over shoals north and east of the Newport Marshes. ⊛ = dye release (Station 11). CB = Causeway Bridge, CPT = Crab Point Thoroughfare, NM = Newport Marshes, PI = Phillips Island.

Table 2. Results of Experiment 2. Instantaneous slug injection of 14.0 liters of Rhodamine - WT solution at Station 11 at low water (LW)+3 hr. The concentration of Rhodamine - WT in seawater is presented with respect to tidal period, depth in the water column, location and salinity. * = Core Creek Bridge.

| Time hr | Time min | Depth Surface | Depth 2 m | Station No. | Salinity °/oo | Conc. ppb |
|---|---|---|---|---|---|---|
| December 12, 1980 | | | | | | |
| LW+2 | 54 | | x | 11 | | 0.0 |
| LW+2 | 54 | x | | 11 | | 0.0 |
| LW+3 | 1 | x | | 12 | 34.02 | 0.0 |
| LW+3 | 4 | | x | 11 | | 1.50 |
| LW+3 | 4 | x | | 11 | | 7.0 |
| LW+3 | 8 | x | | 12 | 33.45 | 1.05 |
| LW+3 | 24 | x | | * | 17.88 | 0.0 |
| LW+3 | 29 | x | | 15 | 34.56 | 0.0 |
| LW+3 | 29 | | x | 14 | 34.56 | 0.0 |
| LW+3 | 29 | x | | 14 | 34.02 | 0.0 |
| LW+3 | 35 | | x | 14 | | 130.0 |
| LW+3 | 35 | x | | 14 | | 0.0 |
| LW+3 | 39 | x | | 9 | 33.00 | 0.0 |
| LW+3 | 43 | x | | 32 | 34.02 | 0.0 |
| LW+3 | 52 | x | | 33 | 33.45 | 0.0 |
| LW+3 | 53 | x | | 18 | 33.45 | 00.0 |
| LW+3 | 53 | x | | 17 | 32.94 | 10.0 |
| LW+3 | 58 | x | | 16 | 34.02 | 5.0 |
| LW+3 | 58 | x | | 32 | 34.56 | 0.0 |
| LW+3 | 59 | x | | 26 | 34.56 | 0.0 |
| LW+4 | 6 | x | | 20 | 34.56 | 0.0 |
| LW+4 | 6 | x | | 15 | 33.45 | 0.0 |
| LW+4 | 8 | x | | 14 | 33.45 | 0.0 |
| LW+4 | 11 | x | | 12 | 34.02 | 0.0 |
| LW+4 | 15 | x | | 20 | | 0.6 |
| LW+4 | 15 | x | | 19-20 | 32.94 | 0.0 |
| LW+4 | 17 | x | | 32 | 34.02 | 0.0 |
| LW+4 | 18 | | x | 19-20 | | 7.0 |
| LW+4 | 20 | x | | 33 | 33.45 | 0.0 |
| LW+4 | 24 | x | | 34 | 34.02 | 0.0 |
| LW+4 | 24 | x | | * | 16.74 | 0.0 |
| LW+4 | 29 | x | | 20 | | 10.0 |
| LW+4 | 29 | | x | 20 | | 17.0 |
| LW+4 | 29 | x | | 27 | 34.56 | 0.0 |
| LW+4 | 31 | x | | 19-20 | 34.56 | 7.2 |
| LW+4 | 31 | | x | 19-20 | 34.02 | 9.6 |
| LW+4 | 39 | x | | 21 | 34.56 | 7.5 |
| LW+4 | 39 | | x | 21 | 34.02 | 0.0 |

Page 1 of 6

Table 2. (cont'd)

| Time hr | min | Depth Surface | 2 m | Station No. | Salinity °/oo | Conc. ppb |
|---|---|---|---|---|---|---|
| LW+4 | 39 | x | | 35 | 32.94 | 0.0 |
| LW+4 | 46 | x | | 32 | 33.45 | 0.0 |
| LW+4 | 50 | x | | 36 | | 2.7 |
| LW+4 | 50 | | x | 36 | | 4.9 |
| LW+4 | 53 | x | | 36 | 33.45 | 2.7 |
| LW+4 | 53 | | x | 36 | 31.32 | 3.4 |
| LW+4 | 54 | x | | 51 | 29.16 | 0.0 |
| LW+4 | 55 | x | | 26 | 32.94 | 0.0 |
| LW+4 | 58 | x | | 38 | | 0.0 |
| LW+4 | 58 | | x | 38 | | 0.0 |
| LW+4 | 58 | x | | 38 | 34.56 | 0.0 |
| LW+4 | 58 | | x | 38 | 34.02 | 0.0 |
| LW+4 | 59 | x | | 9 | 34.00 | 0.0 |
| LW+5 | 1 | x | | 53 | 29.16 | 0.0 |
| LW+5 | 7 | x | | 54 | 27.00 | 0.0 |
| LW+5 | 12 | x | | 55 | 27.54 | 0.0 |
| LW+5 | 23 | x | | 53 | 28.08 | 0.0 |
| LW+5 | 24 | x | | 27 | 34.56 | 0.0 |
| LW+5 | 30 | x | | 51 | 29.19 | 0.0 |
| LW+5 | 34 | x | | * | 16.20 | 0.0 |
| LW+5 | 36 | x | | 35 | 33.45 | 0.0 |
| LW+5 | 41 | x | | 43 | 31.80 | 0.0 |
| LW+5 | 54 | x | | 9 | 34.00 | 0.0 |
| LW+5 | 54 | x | | 26 | 34.56 | 0.0 |
| LW+5 | 56 | x | | 35 | 34.02 | 2.2 |
| LW+6 | 3 | x | | 34 | 34.02 | 0.0 |
| LW+6 | 8 | x | | 33 | 34.56 | 0.0 |
| LW+6 | 12 | x | | 32 | 34.56 | 0.0 |
| LW+6 | 17 | x | | 15 | 35.10 | 0.0 |
| LW+6 | 19 | x | | 35 | 33.45 | 1.1 |
| LW+6 | 21 | x | | 12 | 35.64 | 0.0 |
| LW+6 | 24 | x | | 7 | 35.64 | 0.0 |
| LW+6 | 24 | x | | 27 | 35.10 | 0.0 |
| LW+6 | 27 | x | | 4-5 | 33.45 | 0.0 |
| LW+6 | 29 | x | | * | 19.44 | 0.0 |
| HW+0 | 1 | x | | 48 | 34.02 | 1.0 |
| HW+0 | 1 | | x | 48 | 34.02 | 2.4 |
| HW+0 | 1 | x | | 48 | | 0.7 |
| HW+0 | 1 | | x | 48 | | 3.2 |
| HW+0 | 1 | x | | 31 | 35.10 | 0.0 |
| HW+0 | 3 | x | | 28 | 33.45 | 0.0 |
| HW+0 | 7 | x | | 44 | | 1.7 |
| HW+0 | 7 | | x | 44 | | 4.4 |
| HW+0 | 7 | x | | 44 | 33.45 | 2.3 |

Table 2. (cont'd)

| Time hr | min | Depth Surface | 2 m | Station No. | Salinity °/oo | Conc. ppb |
|---|---|---|---|---|---|---|
| HW+0 | 7 | | x | 44 | 33.45 | 2.2 |
| HW+0 | 12 | x | | 44 | | 3.7 |
| HW+0 | 12 | | x | 44 | | 6.2 |
| HW+0 | 12 | x | | 44 | 33.45 | 2.1 |
| HW+0 | 12 | | x | 44 | 34.56 | 4.5 |
| HW+0 | 17 | x | | 9 | 34.50 | 0.0 |
| HW+0 | 20 | x | | 48 | | 0.0 |
| HW+0 | 20 | | x | 48 | | 0.0 |
| HW+0 | 20 | x | | 48 | 32.94 | 0.0 |
| HW+0 | 20 | | x | 48 | 34.02 | 0.0 |
| HW+0 | 22 | x | | 26 | 35.10 | 0.0 |
| HW+0 | 30 | x | | 45 | | 3.3 |
| HW+0 | 30 | | x | 45 | | 6.2 |
| HW+0 | 30 | x | | 45 | 34.56 | 3.1 |
| HW+0 | 30 | x | | 45 | 33.45 | 3.5 |
| HW+0 | 37 | x | | 47 | | 1.7 |
| HW+0 | 37 | | x | 47 | | 2.4 |
| HW+0 | 37 | x | | 47 | 34.56 | 0.9 |
| HW+0 | 37 | | x | 47 | 34.56 | 0.8 |
| HW+0 | 50 | x | | 51 | | 0.0 |
| HW+0 | 50 | | x | 51 | | 0.0 |
| HW+0 | 50 | x | | 51 | 31.80 | 0.0 |
| HW+0 | 50 | | x | 51 | 32.40 | 0.0 |
| HW+0 | 52 | | | 9 | 34.00 | 0.0 |
| HW+0 | 52 | x | | * | 23.22 | 0.0 |
| HW+0 | 57 | x | | 27 | 35.10 | 0.0 |
| HW+0 | 59 | x | | 35 | | 0.0 |
| HW+0 | 59 | x | | 35 | | 0.0 |
| HW+0 | 59 | x | | 35 | 31.32 | 0.0 |
| HW+0 | 59 | | x | 35 | 32.40 | 0.0 |
| HW+1 | 4 | x | | 46 | | 0.0 |
| HW+1 | 4 | | x | 46 | | 0.0 |
| HW+1 | 4 | x | | 46 | 34.56 | 0.0 |
| HW+1 | 4 | | x | 46 | 33.45 | 0.0 |
| HW+1 | 9 | x | | 49 | | 3.2 |
| HW+1 | 9 | | x | 49 | | 7.0 |
| HW+1 | 9 | x | | 49 | 31.80 | 6.7 |
| HW+1 | 9 | | x | 49 | 32.94 | 7.3 |
| HW+1 | 10 | x | | 35 | 34.02 | 0.0 |
| HW+1 | 22 | x | | 26 | 34.56 | 0.0 |
| HW+1 | 45 | x | | 50 | | 2.7 |
| HW+1 | 45 | | x | 50 | | 7.0 |
| HW+1 | 45 | x | | 50 | 32.40 | 2.1 |
| HW+1 | 45 | | x | 50 | 33.45 | 6.5 |

Table 2. (cont'd)

| Time hr | min | Depth Surface | 2 m | Station No. | Salinity °/∘∘ | Conc. ppb |
|---|---|---|---|---|---|---|
| HW+1 | 50 | x | | 48 | | 0.0 |
| HW+1 | 50 | | x | 48 | | 0.0 |
| HW+1 | 50 | x | | 48 | 35.12 | 0.0 |
| HW+1 | 50 | | x | 48 | 34.56 | 0.0 |
| HW+1 | 57 | x | | 27 | 35.10 | 0.0 |
| HW+1 | 57 | x | | * | 26.46 | 0.0 |
| HW+2 | 2 | x | | 9 | 34.00 | 0.0 |
| HW+2 | 15 | x | | 46 | | 0.2 |
| HW+2 | 15 | | x | 46 | | 0.1 |
| HW+2 | 15 | x | | 46 | 33.45 | 2.1 |
| HW+2 | 15 | | x | 46 | 33.45 | 3.9 |
| HW+2 | 20 | x | | 46 | | 5.2 |
| HW+2 | 20 | | x | 46 | | 5.4 |
| HW+2 | 20 | x | | 46 | 34.02 | 3.2 |
| HW+2 | 20 | | x | 46 | 33.45 | 3.8 |
| HW+2 | 22 | x | | 26 | 35.10 | 0.0 |
| HW+2 | 31 | x | | 39 | | 0.6 |
| HW+2 | 31 | | x | 39 | | 1.1 |
| HW+2 | 31 | x | | 39 | 35.12 | 0.8 |
| HW+2 | 31 | | x | 39 | 34.02 | 0.8 |
| HW+2 | 37 | x | | 41 | 34.02 | 0.0 |
| HW+2 | 37 | | x | 41 | 33.45 | 0.0 |
| HW+2 | 52 | x | | 27 | 35.10 | 0.0 |
| HW+2 | 52 | x | | * | 31.32 | 0.0 |
| HW+2 | 56 | x | | 35 | 32.94 | 0.0 |
| HW+2 | 56 | | x | 35 | 29.70 | 0.0 |
| HW+3 | 7 | x | | 9 | 34.50 | 0.0 |
| HW+3 | 15 | x | | 34 | 34.02 | 0.0 |
| HW+3 | 22 | x | | 27 | 34.02 | 0.0 |
| HW+3 | 29 | x | | 43 | 31.32 | 0.0 |
| HW+3 | 35 | x | | 39 | 34.02 | 0.2 |
| HW+3 | 46 | x | | 12 | 34.56 | 0.0 |
| HW+3 | 52 | x | | 27 | 35.10 | 0.0 |
| HW+3 | 55 | x | | 14 | 34.56 | 0.0 |
| HW+3 | 55 | x | | 14 | | 0.0 |
| HW+3 | 55 | | x | 14 | | 0.0 |
| HW+4 | 4 | x | | 25 | 33.45 | 0.0 |
| HW+4 | 7 | x | | * | 29.16 | 0.0 |
| HW+4 | 12 | x | | 9 | 34.00 | 0.0 |
| HW+4 | 13 | x | | 29 | 34.56 | 0.0 |
| HW+4 | 49 | x | | 29 | 35.10 | 0.0 |
| HW+4 | 49 | | x | 29 | | 0.0 |
| HW+4 | 49 | x | | 29 | | 0.0 |
| HW+4 | 52 | x | | 27 | 33.45 | 0.0 |

Table 2. (cont'd)

| Time hr | min | Depth Surface | 2 m | Station No. | Salinity °/₀₀ | Conc. ppb |
|---|---|---|---|---|---|---|
| HW+4 | 58 | x | | 31 | 34.56 | 0.0 |
| HW+5 | | x | | * | 28.08 | 0.0 |
| HW+5 | 17 | x | | 9 | 34.00 | 0.0 |
| HW+5 | 52 | x | | 27 | 34.56 | 0.0 |
| HW+6 | 7 | x | | 9 | 34.00 | 0.0 |
| HW+6 | 7 | x | | * | 29.16 | 0.0 |
| LW+0 | 39 | x | | 27 | 33.45 | 0.0 |
| LW+0 | 44 | x | | * | 30.24 | 0.0 |
| LW+1 | 42 | x | | * | 29.70 | 0.0 |
| LW+2 | 41 | x | | * | 26.46 | 0.0 |
| LW+3 | 13 | x | | 27 | 34.02 | 0.0 |
| LW+3 | 44 | x | | * | 22.68 | 0.0 |
| LW+4 | 39 | x | | 27 | 35.10 | 0.0 |
| LW+4 | 41 | x | | * | 22.68 | 0.0 |
| LW+5 | 20 | x | | 27 | 34.02 | 0.0 |
| LW+5 | 40 | x | | * | 25.38 | 0.0 |
| December 13, 1980 | | | | | | |
| HW+ | 24 | x | | * | 25.92 | 0.0 |
| HW+1 | 28 | x | | * | 30.78 | 0.0 |
| HW+2 | 33 | x | | * | 30.24 | 0.0 |
| HW+3 | 23 | x | | * | 30.24 | 0.0 |
| HW+4 | 33 | x | | * | 31.80 | 0.0 |
| HW+5 | 29 | x | | * | 29.70 | 0.0 |
| LW+ | 36 | x | | * | 31.32 | 0.0 |
| LW+1 | 29 | x | | * | 30.78 | 0.0 |
| LW+2 | 29 | x | | * | 28.08 | 0.0 |
| LW+3 | 29 | x | | * | 29.70 | 0.0 |
| LW+4 | 29 | x | | * | 25.92 | 0.0 |
| LW+5 | 29 | x | | * | 29.70 | 0.0 |
| HW+0 | 2 | x | | * | 29.16 | 0.0 |
| HW+1 | 2 | x | | * | 28.08 | 0.0 |
| HW+2 | 1 | x | | 25 | 32.40 | 0.0 |
| HW+2 | 1 | | x | 25 | 33.45 | 0.0 |
| HW+2 | 2 | x | | * | 28.62 | 0.0 |
| HW+2 | 17 | x | | 14 | 33.45 | 0.0 |
| HW+2 | 29 | x | | 41 | 32.94 | 0.0 |
| HW+2 | 45 | x | | 27 | 34.56 | 0.0 |
| HW+2 | 32 | x | | 30 | 35.10 | 0.0 |
| HW+3 | 2 | x | | * | 30.24 | 0.0 |
| HW+3 | 7 | x | | * | 30.24 | 0.0 |
| HW+4 | 12 | x | | * | 31.32 | 0.0 |
| HW+5 | 12 | x | | * | 31.24 | 0.0 |

Table 2 (cont'd)

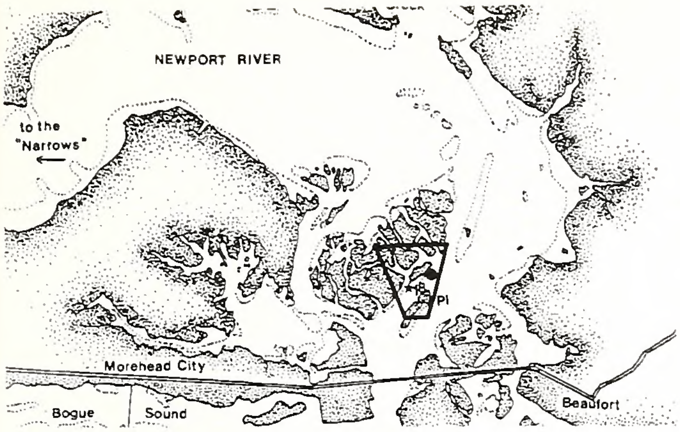
| Time hr | min | Depth Surface | 2 m | Station No. | Salinity °/₀₀ | Conc. ppb |
|---|---|---|---|---|---|---|
| LW+0 | 51 | x | | * | 30.24 | 0.0 |
| LW+1 | 46 | x | | * | 31.32 | 0.0 |
| LW+2 | 51 | x | | * | 31.32 | 0.0 |
| LW+3 | 51 | x | | * | 31.32 | 0.0 |
| LW+4 | 51 | x | | * | 31.32 | 0.0 |
| LW+5 | 52 | x | | * | 30.78 | 0.0 |
| December 14, 1980 | | | | | | |
| HW+0 | 26 | x | | * | 30.78 | 0.0 |
| HW+1 | 27 | x | | * | 30.78 | 0.0 |
| HW+2 | 41 | x | | * | 29.70 | 0.0 |
| HW+3 | 52 | x | | * | 30.78 | 0.0 |
| HW+4 | 56 | x | | * | 30.78 | 0.0 |
| HW+5 | 41 | x | | * | 31.32 | 0.0 |
| LW+0 | 49 | x | | * | 30.24 | 0.0 |
| LW+2 | 29 | x | | * | 27.00 | 0.0 |
| LW+3 | 29 | x | | * | 23.76 | 0.0 |
| LW+4 | 29 | x | | * | 22.68 | 0.0 |
| HW+0 | 2 | x | | * | 25.38 | 0.0 |

Photograph 1.

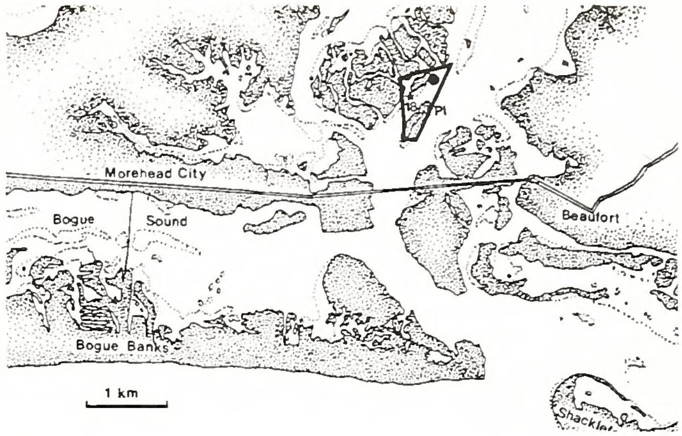
Photograph 2.

Photograph 3.

Photograph 4.

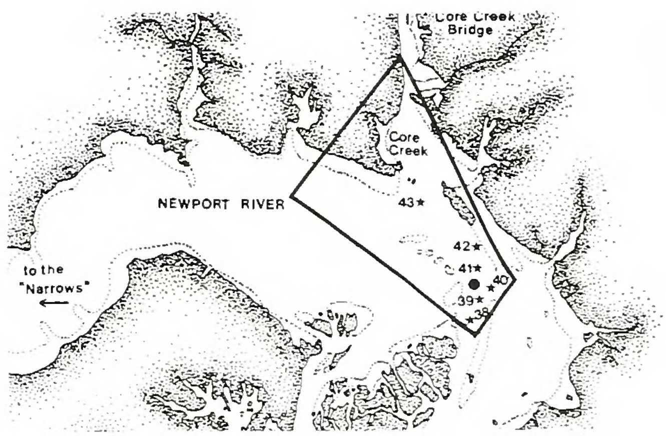



**Photograph 1.** Aerial photograph of dye plume in the Atlantic Intracoastal Waterway channel during Experiment 2, December 12, 1980, LW + 4 hrs. Taken from approximately 350 m.




**Photograph 2.** Aerial photograph of dye plume generally within the eastern border of the Atlantic Intracoastal Waterway channel near Phillips Island during Experiment 2, December 12, 1980, LW + 4 hrs. Taken from approximately 350 m.


**Photograph 3.** Aerial photograph of dye plume near the west bank of Phillips Island during Experiment 2, December 12, 1980, LW + 4 hrs. Taken from approximately 150 m.




**Photograph 4.** Aerial photograph of dye plume over shoals northeast of the Newport Marshes and southeast of Core Creek during Experiment 2, December 12, 1980, slack high water. Taken from approximately 350 m.

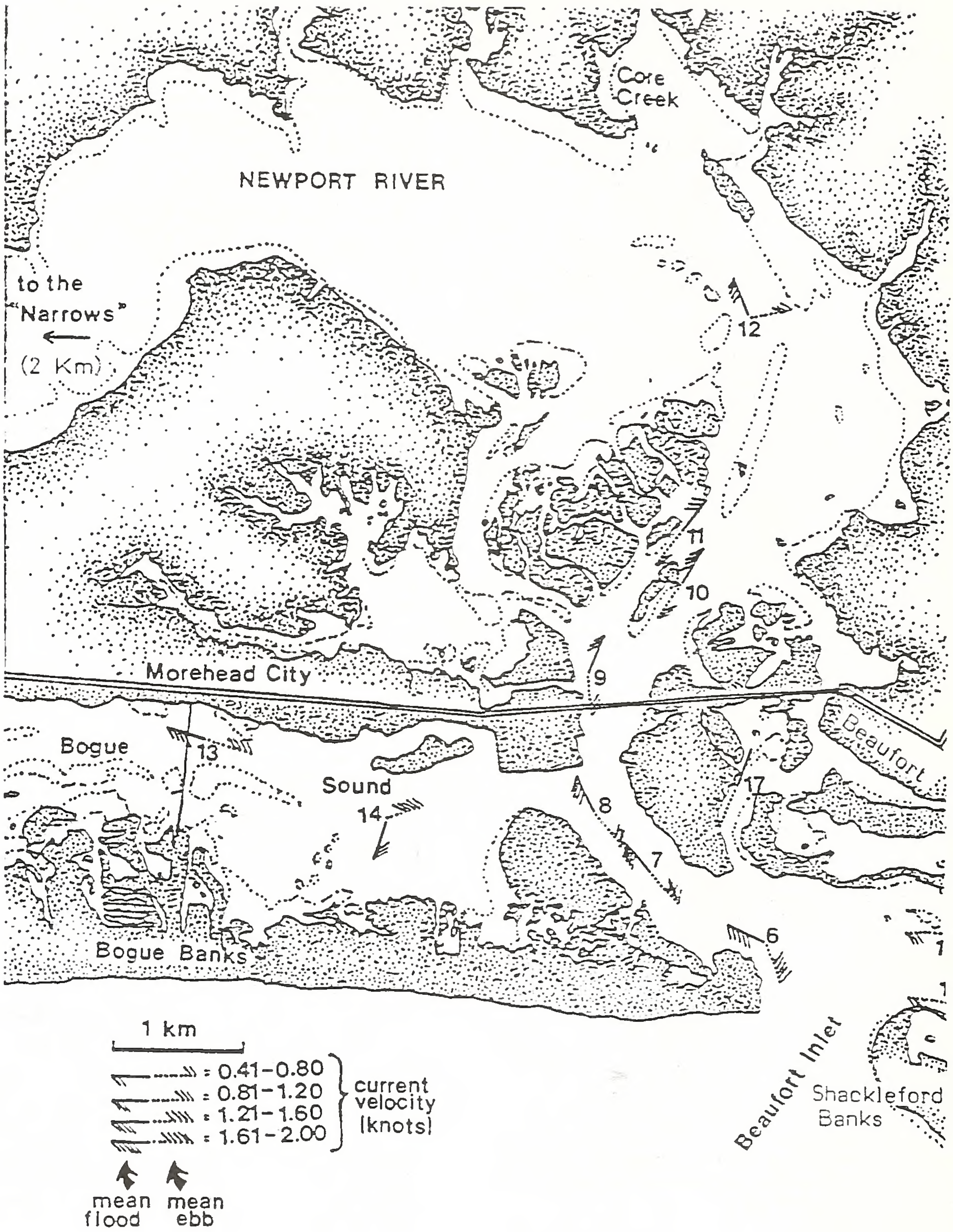



Figure 8. Current meter data (U.S. Geological Survey 1976). Data in Appendices C.1-C.3.

current flowing 44° (true) on the flood and 215° (true) on the ebb with a mean velocity of 1.39 knots on the flood and 1.15 knots on the ebb. Data from two stations in the Intracoastal Water (Stations 9 and 11) show a reversing current flowing NE-SW with mean velocities of approximately 1 knot on both flood and ebb. These data correspond closely with the information derived from the dye survey.

## DISCUSSION

Experiments 1 and 2 reveal that the Intracoastal Waterway and the deep-water access channel to the port greatly influences tidal water movement in the Newport River estuary. In the process of defining this estuarine complex as "well-mixed" much consideration should be given to the effect of the Intracoastal Waterway channel on horizontal advection in the estuary. In Experiment 1, during the ebb tide, the dye plume released to the north of Newport Marshes, outside the boundaries of the Intracoastal Waterway, moved eastwards into the main channel of the Intracoastal Waterway. It then moved seaward as a relatively discrete body of water to the east of Newport Marshes, west of Phillips Island, and under the Morehead City Causeway Bridge. At this last point, horizontal dispersion occurred due to the eddy effects of the bridge supports before the tracer water moved out towards the Beaufort Inlet. A small fraction of the initial dye release passed down the Crab Point Thoroughfare to the west of Newport Marshes. Thus, on an ebbing tide, water moves seawards in the channels as a discrete mass but it becomes mixed into other water masses and diluted before reaching the Beaufort Inlet. If the release point had been further west more dye may have passed through the Crab Point Thoroughfare.

On the flood tide during Experiment 1 there was a horizontal movement of water through all the major channels near the Beaufort Inlet. The dye release was rapidly diluted and the water penetrated Bogue Sound, Bulkhead Channel, Taylor's Creek, Gallants Channel, and Crab Point Thoroughfare as well as following the Intracoastal Waterway. Once in these channels, the water moved as a discrete body as evidenced by the passage of dye released just south of Causeway Bridge during a flood tide (Experiment 2). These data suggest that any material suspended or dissolved in the water near Beaufort Inlet may be carried up any or all of the channels that branch off from this body of water and possibly will enter the water of Bogue and Back Sounds and Taylors Creeks as well as the main body of the Newport River estuary.

The data presented here suggest that even if a discrete body of water passes down the Intracoastal Waterway on the ebb and is retained in Beaufort Inlet, rather than being released to the open sea, the water will be dispersed throughout all the channels inland of Beaufort Inlet on the next flood tide.

The presence of dye near the nursery area (Station 51) is of significance. If the traced water detected in this area in Experiment 1 is of the same plume which left the Newport River estuary during the ebbing tide, a distance of 14 miles was traversed in one tidal cycle. The Newport

Marshes were inaccessible to our boats, and it is unknown whether or not the traced water entered the marsh area. It is possible that traces of dye which may have entered the Newport Marshes could account for the concentration of dye found near the nursery area (Table 1). The high flushing rate up to Station 51 corresponds to findings made by Hyle (1976) in which the relative changes in volume between high and low water in segments from Crab Point to the Morehead City Causeway Bridge are the same. The volume changes west of Crab Point sharply decrease and may explain Hyle's low average flushing rate of 12.0 tidal cycles. For the whole estuary the similarity between dye plume movement during the ebbing tide in Experiment 1 and flooding tide in Experiment 2 north of the Newport Marshes is evidence that a northwest/southeast flow exchanges water in the nursery area in the upper end of the estuary with that of the Intracoastal Waterway.

## REFERENCES


Ducharme, A. and J. Strickland. 1980. The Living Resources of the Newport River. Unpublished manuscript, Duke University Marine Laboratory.

Hyle, R.A., II. 1976. Fishes of the Newport River estuary, North Carolina, their composition, seasonality and community structure, 1970-72. Ph.D. thesis, University of North Carolina, Chapel Hill. 102 pp.

U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Survey. March, 1981. Nautical Chart #11541.

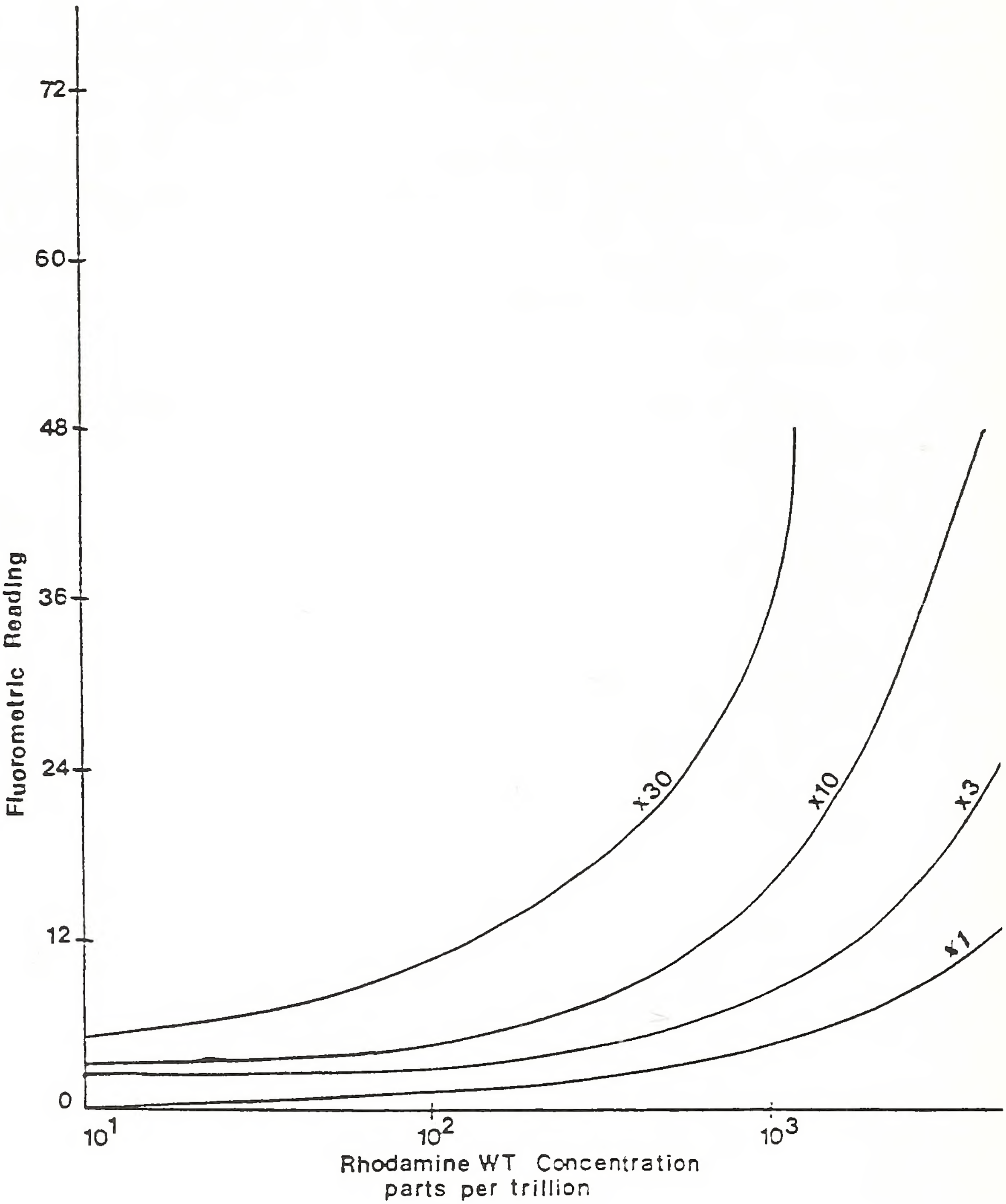
U.S. Geological Survey. 1971. 7.5 minute series (topographic) of Beaufort Quadrangle. Map #N3437.5-W7637.5/7.5.

U.S. Geological Survey. 1976.

Wolfe, D.A. 1975. Modeling the distribution and cycling of metallic elements in estuarine ecosystems. In Estuarine Research, ed. L.E. Cronin, Vol. 1, pp. 645-671.

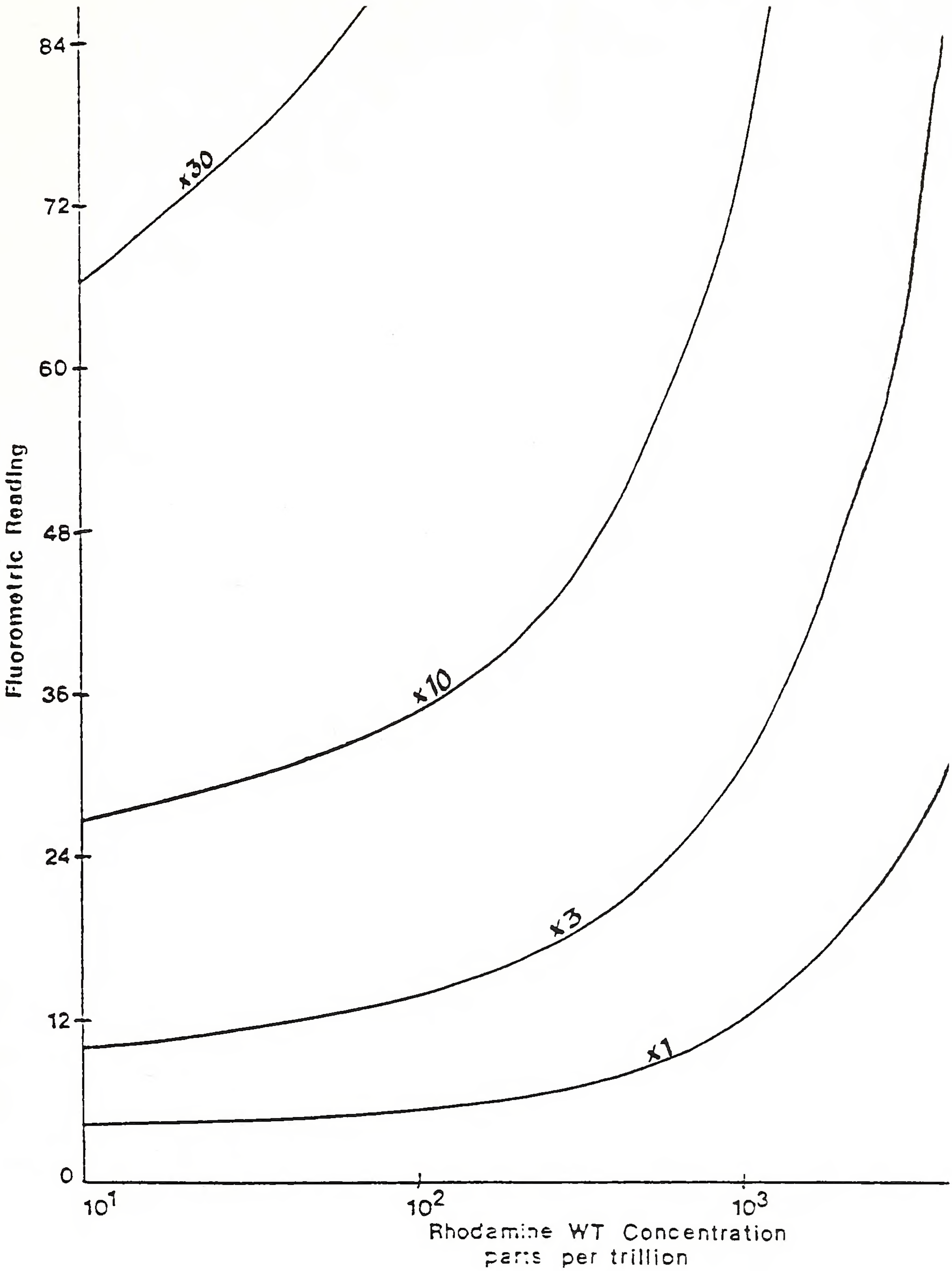
Wolfe, D.A., F.A. Cross, and C.D. Jennings. 1973. The flux of Mn, Fe, and Zn in an estuarine ecosystem. In Radioactive Contaminants of the Marine Environment, pp. 159-175. Vienna: International Atomic Energy Agency.

Williams, A.B. 1966. Annual phytoplankton production in a system of shallow temperate estuaries. In Some Contemporary Studies in Marine Science, ed. H. Barnes, pp. 669-716. London: George Allen and Unwin Ltd.



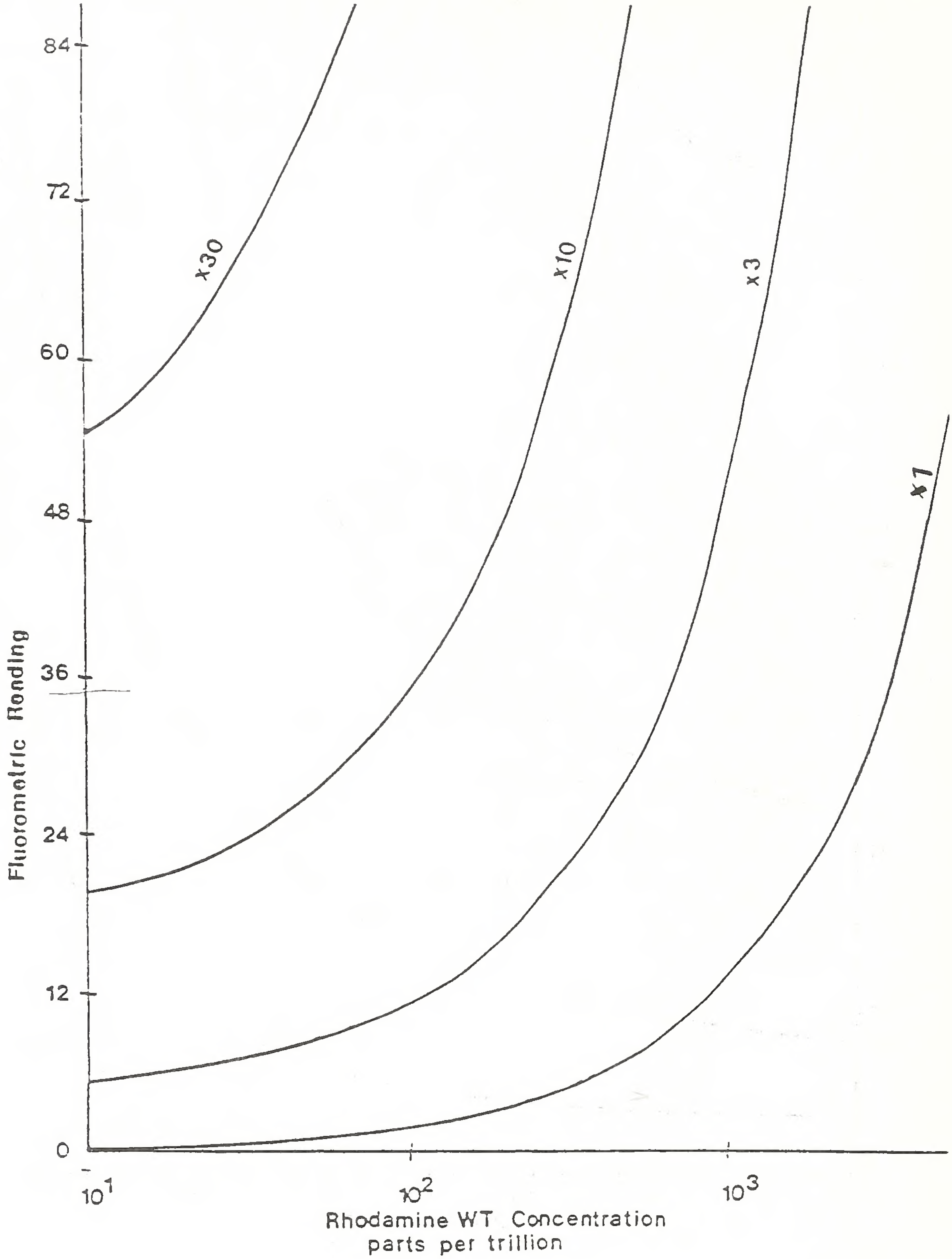

Appendix A.1. Fluorometric calibration curves.

Experiment 1. Surface flow-through water sampling calibration curve.



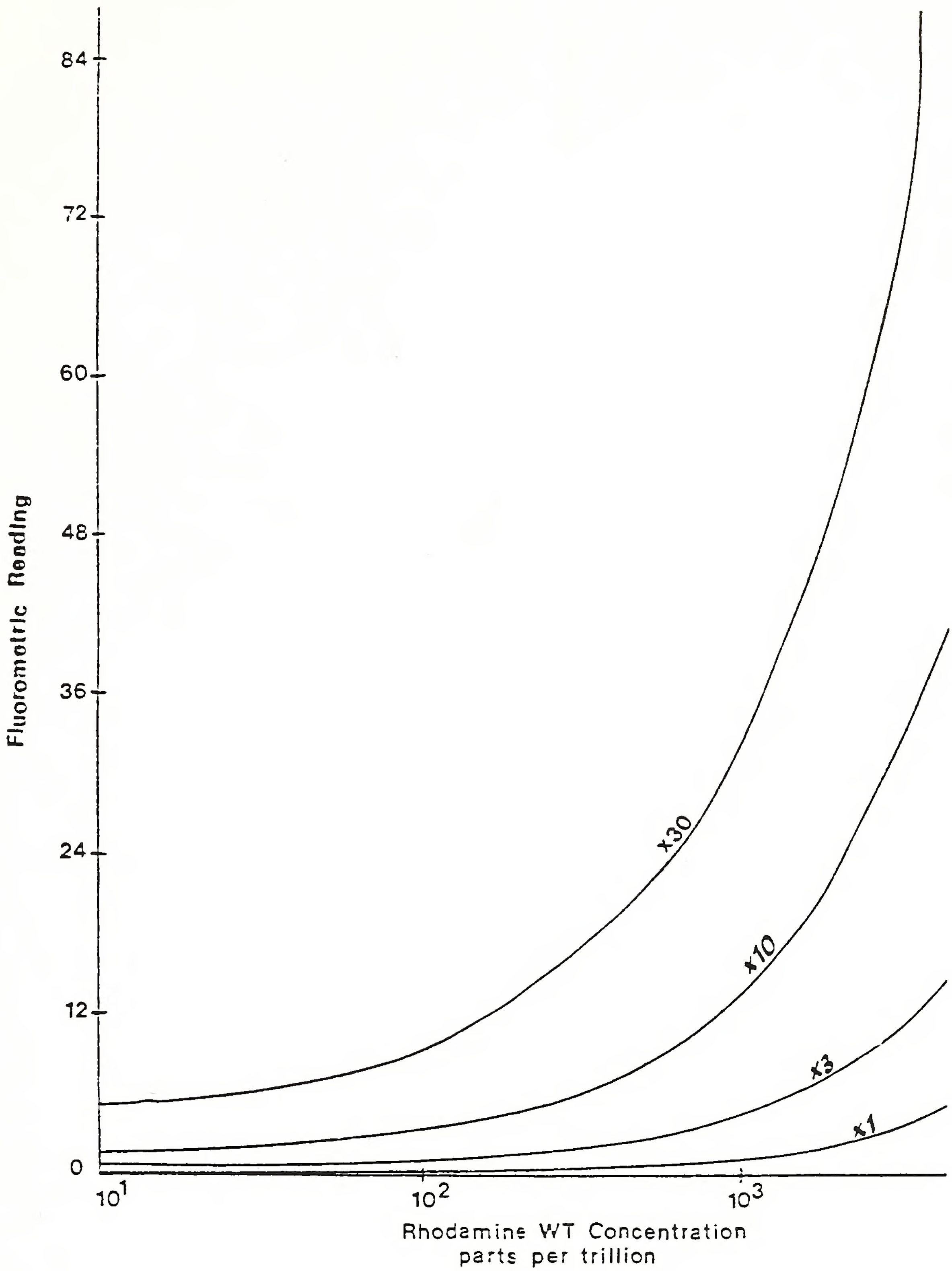

Appendix A.2. Fluorometric calibration curves.

Experiment 2. Surface flow-through water sampling calibration curve.




Appendix A.3. Fluorometric calibration curves.

Experiment 2. 2 m flow-through water sampling calibration curve.




Appendix A.4. Fluorometric calibration curves.

Experiments 1 and 2. Surface cuvette water sampling calibration curve.

Appendix B. USGS Tide Table. Adjusted for Morehead City-Beaufort Causeway Bridge from Hampton Roads, VA data.

| 1980 | | Time (h.m.) |
|---|---|---|
| November 20 | high | 0559 |
| | low | 1211 |
| | high | 1825 |
| November 21 | low | 0020 |
| | high | 0654 |
| | low | 1306 |
| | high | 1918 |
| December 12 | low | 0436 |
| | high | 1108 |
| | low | 1721 |
| | high | 2337 |
| December 13 | low | 0531 |
| | high | 1158 |
| | low | 1809 |
| December 14 | high | 0036 |
| | low | 0631 |
| | high | 1256 |
| | low | 1905 |
| December 15 | high | 0136 |
| | low | 0740 |
| | high | 1359 |
| | low | 2005 |

Appendix C.1. Description of current meter stations for Atlantic Intracoastal Waterway. U.S. Geological Survey, 1976.

| Station No. | Location: Latitude (N) | Location: Longitude (W) | Depth of water (ft)(MLW) | Depth of meter (ft) | Beginning of data | Duration of data (days) |
|---|---|---|---|---|---|---|
| 6 | 34°41.98' | 76°40.52' | 25 | 10 | 3/30/76 | 16 |
| 6 | 34°41.98' | 76°40.52' | 25 | 20 | 3/30/76 | 16 |
| 7 | 34°42.23' | 76°41.17' | 27 | 6 | 2/25/76 | 70 |
| 7 | 34°42.23' | 76°41.17' | 27 | 15 | 2/25/76 | 70 |
| 8 | 34°42.78' | 76°41.65' | 34 | 6 | 3/11/76 | 16 |
| 8 | 34°42.78' | 76°41.65' | 34 | 15 | 3/11/76 | 16 |
| 9 | 34°43.37' | 76°41.63' | 22 | 6 | 4/13/76 | 17 |
| 10 | 34°43.88' | 76°41.00' | 24 | 6 | 2/23/76 | 33 |
| 10 | 34°43.88' | 76°41.00' | 24 | 15 | 2/23/76 | 33 |
| 11 | 34°44.17' | 76°40.83' | 20 | 6 | 4/14/76 | 17 |
| 12 | 34°45.45' | 76°40.42' | 20 | 6 | 4/17/76 | 17 |
| 13 | 34°43.00' | 76°43.97' | 19 | 6 | 2/24/76 | 32 |
| 14 | 34°42.70' | 76°42.83' | 15 | 6 | 2/23/76 | 33 |
| 17 | 34°42.70' | 76°40.78' | 15 | 6 | 2/24/76 | 32 |
| 18 | 34°42.03' | 76°39.23' | 19 | 6 | 3/17/76 | 13 |
| 19 | 34°41.53' | 76°39.13' | 22 | 6 | 2/25/76 | 34 |
| 20 | 34°42.13' | 76°37.05' | 13 | 6 | 4/24/76 | 9 |

Appendix C.2. Results of current meter experiments for Atlantic Intracoastal Waterway. U.S. Geological Survey, 1976.

| Station No. | Mean flood | | Mean ebb | |
|---|---|---|---|---|
| | Velocity (knots) | Direction (°) | Velocity (knots) | Direction (°) |
| 6(10') | 1.96 | 307 | 2.77 | 151 |
| 6(20') | 1.99 | 320 | 1.71 | 153 |
| 7( 6') | 1.35 | 314 | 1.52 | 145 |
| 7(15') | 1.64 | 305 | 1.71 | 128 |
| 8( 6') | 1.30 | 327 | 1.00 | 144 |
| 8(15') | 1.20 | 334 | 1.00 | 138 |
| 9( 6') | 1.01 | 054 | 1.02 | 185 |
| 10( 6') | 1.39 | 044 | 1.15 | 215 |
| 10(15') | 1.31 | 044 | 1.16 | 226 |
| 11( 6') | 0.95 | 040 | 0.97 | 224 |
| 12( 6') | 1.50 | 075 | 1.20 | 350 |
| 13( 6') | 1.43 | 293 | 1.45 | 110 |
| 14( 6') | 1.14 | 266 | 1.63 | 094 |
| 17( 6') | 1.19 | 022 | 1.17 | 202 |
| 18( 6') | 0.83 | 126 | 0.82 | 304 |
| 19( 6') | 1.34 | 135 | 1.11 | 305 |
| 20( 6') | 0.87 | 080 | 1.29 | 262 |

Appendix C.3. Results of current meter experiments for Atlantic Intracoastal Waterway. U.S. Geological Survey, 1976.

| Station No. | Minimums: Before flood Velocity (knots) | Minimums: Before flood Direction (°) | Minimums: After flood Velocity (knots) | Minimums: After flood Direction (°) | Nontidal Velocity (knots) | Nontidal Direction (°) |
|---|---|---|---|---|---|---|
| 6(10') | 0.09 | 232 | 0.04 | 225 | 0.23 | 228 |
| 6(20') | 0.20 | 242 | 0.09 | 232 | 0.15 | 237 |
| 7( 6') | 0.03 | 054 | 0.03 | 227 | 0.16 | 172 |
| 7(15') | 0.05 | 222 | 0.09 | 220 | 0.10 | 154 |
| 8( 6') | 0.01 | 218 | 0.10 | 237 | 0.07 | 334 |
| 8(15') | 0.06 | 048 | 0.05 | 237 | 0.13 | 018 |
| 9( 6') | 0.20 | 127 | 0.14 | 122 | 0.33 | 128 |
| 10( 6') | 0.05 | 130 | 0.04 | 126 | 0.09 | 114 |
| 10(15') | 0.03 | 317 | 0.01 | 313 | 0.03 | 321 |
| 11( 6') | 0.02 | 309 | 0.01 | 130 | 0.09 | 236 |
| 12( 6') | 0.48 | 031 | 0.50 | 341 | - | - |
| 13( 6') | 0.00 | 027 | 0.03 | 028 | 0.08 | 090 |
| 14( 6') | 0.01 | 179 | 0.02 | 175 | 0.19 | 111 |
| 17( 6') | 0.03 | 113 | 0.02 | 116 | 0.05 | 168 |
| 18( 6') | 0.03 | 033 | 0.06 | 217 | 0.02 | 278 |
| 19( 6') | 0.06 | 218 | 0.02 | 219 | 0.10 | 182 |
| 20( 6') | 0.06 | 359 | 0.03 | 163 | 0.18 | 268 |